Theses of the Doctoral Dissertation entitled

Glacier reconstruction in the Rodna Mts. based on field and GIS methods

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Budapest, 2015

1. Introduction

The Earth's climate and environment characteristic of the constant changes (Goudie, 2004). In order to understand the complexities of global processes that affect us, targeted basic researches must be done to input this highly variable and complex system. However, many researches have no sharp boundary, but overlapped and sometimes blurred in other researches. This is especially true in the case of complex issues such as global climate change.

Glacial landforms provide excellent evidence of past environmental changes since glaciers have a close relationship with climate (e.g. Ohmura et al., 1992; Nesje and Dahl, 2000). Glaciers have attracted increasing scientific and public interest as indicators of present and past climate change (Knoll and Kerschner, 2009). Since glaciers are in a sensitive weight and energy ratio with environment, rapidly reply for the changes in it. In particular, it can be detected today in the Alps in the neighbour of the Carpathian Basin. Thus, paleoglaciers represent one of the most important records of past climatic changes over the past two decades in Eurasia (Knoll and Kerschner, 2009). The climatic trends described in the Alps, proceeded in different mechanisms and ways in the Carpathians and in some cases occurred in other time (Makos et al., 2013; Popa and Bouriaud, 2014; Ruszkiczay-Rüdiger et al., 2015). Due to different behaviour more focus is placed on researches in the Carpathian regional studies.

Glacier retreats and quantitative/qualitative changes in melting of ice are coupled with GIS and remote sensing methods over the last few decades in the Alps. In the existence of recent forms, or a large amount of data the synthesis is simple. However, in their absence, the research promises a lot more challenges, starting with data collection, their new, site-specific processing through to evaluation. Many of these untapped opportunities are in the area of the Romanian Carpathians such as Rodna Mountains.

2. Objectives

- Provide the first modern, detailed glacial geomorphological survey of the study area.
- Pursue the first decades of the 20th century Hungarian and the '70s Romanian researcher's professional work in. Validate their authenticity.

- Switch line my examinations in the Carpathians on going environmental reconstruction studies.
- Integrate field measurements, the newly produced geospatial data (self-created digital elevation model (DEM)) and the existing remote sensing data (orthophotos) in an integrated Geographical Information System (GIS) environment.
- To carry out the integrated GIS environment offered calculations, which are essential for the comparison with other areas. Derived data: equilibrium line altitudes, glacier extents, ice flow, ice thickness shear stress.
- Testing methods in a small representative pilot area to be carried out in the entire mountain range.
- Dating by lichenometry; mapping landforms of Little Ice Age (LIA).
- Another method is based on a solid foundation upon geomorphological dating. This allows the Rodna Mountains detected climate / environment changes compare with other areas of Eurasian orogen, for example with the Central and Northern Balkans, where these tests have been carried out.
- The reconstructions give a more complete framework for understanding of the Carpathian-Balkan region present and past environmental changes.
- The development of a uniform, filling a gap in the domestic specialty methodology that allows the adaptation of the methodology and processing similar geomorphological data of other study areas

3. Material and Methods

For the most complex research, multi-year field work was combined with GIS to carry out an exact and comprehensive calculation (Smith and Clark, 2005).

3.1. Fieldwork

All geomorphological evidence of glaciation and locations of lichenometric measurements were mapped using handheld GPS receivers (Milivojevic et al., 2008) in three sample sites (Zănoaga Mare-, Zănoaga Iezerului- and Western Buhăescu valley).

3.2. Glacier extents

Glacier extent was traced with the help of all calibrated field measurements of marginal forms and field photos. A DEM (Clark, 1997; Kuhlemann et al., 2005), high-resolution orthophoto (Knoll and Kerschner, 2009) and technical literature supported the explanation (Meierding, 1982).

3.3. Glacier surface and paleo equilibrium line

Contours for glacier polygons were edited to prepare a three-dimensional reconstruction of the glaciers, which surfaces and equilibrium line altitudes (ELA) are the basis for accurate paleoglacier surface estimation.

In manual reconstruction using the available geomorphological evidence determined the contour of the paleoglacier, and taking into account the specific glacial dynamical basic fundamentals and relief the glacier surface contours were derived. The three-dimensional glacier surface was modelled by numerical modelling according to Benn and Hulton (2010) relationships and number of factors.

The glacier reconstruction based equilibrium line altitude and its vertical changing is an extremely important climate change indicator. The ELA is one of the most common and most important glacier parameters to characterise climate conditions in present and past mountain areas. In my studies four pELA reconstruction methods were used:

- Maximum Elevation of Lateral Moraines (MELM)
- Toe-to-Headwall Altitude Ratio (THAR)
- Accumulation-area Ratio (AAR)
- Size specific Accumulation-area Ratio (ssAAR)

3.4. Ice thickness and ice volume estimation

Ice volume can be derived from the three-dimensional ice surface reconstruction (Chen and Ohmura, 1990; Bahr et al, 1997) to which the Chen and Ohmura empirical equation was used. Ice thickness values were also estimated with GIS software for the most extensive glacier phase.

3.5 Lichenometry

Rhizocarpon geographicum lichens longest axes were measured and growth rate was derived from the diameters which were used to date the moraines. Since there was no growth rate for the Rodna Mountains, I used High Tatras' (Kotarba, 1988) due to petrographic, aspect and climatic similarities.

3.6. Data processing in GIS environment

All input vector and raster data were storaged, analysed and the geodatabase compilation, glacier reconstruction, derived data calculation, cartographic outputs (including the photorealistic visualization as well) were processed in an integrated GIS with the software package ArcGIS (Clark et al., 2004). A DEM was derived (Cowton et al., 2009; Telbisz et al., 2013) from a 10 m contour distance georeferenced Stereo-70 1.25 000 Romanian topographic map. Four former paleoglaciation maps (Szilády, 1907; Sawicki, 1911; Sîrcu, 1978 and Gheorghiu, 2012) covering the study area were georeferenced and digitised to compare with my results.

4. Results and conclusions

4.1. Results of glacial-geomorphological mapping

Detailed field surveys were carried out in three valleys on the northern flank of the western Rodna Mountains. Glacial landforms in the north-eastern and north aspected valleys of the study area are well preserved. Zănoaga Mare and Zănoaga Iezerului valley are similar in morphology, both are narrow and can be divided into two parts separated with a rugged valley-floor step at 1750 m, the upper part is characterized by landforms of former cirque and rock glaciers.

The significantly longer Buhăescu valley has a more complex plateau like catchment area. The lowest terminal moraine position is 1146 m in the Zănoaga Mare, 1235 m in the Zănoaga Iezeruli and 1086 m in the Buhăescu valley. Based on field measurements glacial-geomorphological mapped was edited

4.2. Glacier extents based on morphology and glacial-dynamics

Glacial-geomorphological map and glacial-dynamical relationships were used to reconstruct former glacier extents. Five generations of paleoglaciers were determined in Zănoaga Mare valley. Reconstruction of the three upper cirque glaciers (Zănoaga Mare 5, 4 and 3) are very simple thanks to favourable valley morphology. In this valley the two longest advances, Zănoaga Mare 2 and Zănoaga Mare 1 extents were reconstructed by lateral and terminal moraine ridges. Five glacier generations were observed in the Zănoaga Iezerului valley. Glacier reconstruction of the upper section forms above 1760 m is more difficult as moraines are affected by periglacial processes.

The maximum length of the longest Buhăescu Mare 1 glacier from the ridge to its terminal moraine at 1090 m was about 4.2 km. It is the largest reconstructed glacier with area of 5 km^2. At this extent a big plateau like glacier or icefield (Finlayson et al., 2009) on its upper part existed and stretched along the valley which shows a more typically U-shaped cross section on its lower part. The situation was very similar during the extent of Buhăescu Mare 2 glacier, but with a smaller area (3.2 km^2) and a shorter length, 2.3 km).Three other series were mapped closer to the ridge but with less extensive accumulation area. The accumulation forms found in the Buhăescu valley at 1972 and 1977 m are better conserved, more intact.

Glacier extents were reconstructed by terminal moraines. Glacier area for the B2/1 is 0.025 km^2, while 0.014 km^2 for B3/1.

After glacial-geomorphological mapping five glacier generations were reconstructed in the northern valleys of the north-western Rodna Mountains: (starting from the largest): Rebra, Zănoaga Iezerului, Iezerele Buhăescu, Buhăescu Mare, and Zănoaga Mare.

4.3. Results of glacier surface reconstruction methods

Various glacial-geomorphological data calculations (pELA, volume, area and ice thickness) were based on reconstructed glacier surfaces which facilitate a reliable modelling. Four types of paleoglacier surface reconstructions were used.

The manual was used for all reconstructed (20 pieces) glaciers, while the numerical procedure was carried out only the glaciers of the Rebra phase, due to their size make clearly visible differences between the calculations. The three-dimensional paleoglacier surface reconstruction was carried out by interpolation from the manually defined contours or by modelled longitudinal and cross sections along the flowline, as well as the use of DEM.

Verification of the glacier surfaces was carried out by glacio-dymanical relationships field measurements, and the use of scientific literatures (Goudie, 2004; Lukas, 2006; Benn and Evans, 2010; Benn and Hulton 2010) and a comparative review of existing Alpine glacier. Numerical modelling methods are currently the most advanced, most accurate and quantitative analyses and closest to GIS environment.

4.4. Glacier equilibrium line altitude, volume and average thickness

pELA estimation was carried out with the following approaches: AAR (with two ratios), MELM, THAR and size-specific accumulation-area ratio (ratios: 0.34-0.59). The Rebra phase records the most extended mapped glaciation of the study area with an average pELA of 1765 m while the second (Zănoaga Iezerului) shows an average pELA of 1865 m. The third phase (Iezerele Buhăescu) was less extensive and had a 1960 m average ELA. Buhăescu Mare and Zănoaga Mare have average pELA altitude of 2001 and 2025 m.

Between the youngest and the oldest phase the area difference were seven times, while twice between average ice thickness calculations and were seventeen times in the ice volumes using Chen and Ohmura relationship while nearly thirty times based on GIS analysis. 188 meters were the maximum ice thickness at Buhăescu Mare 1 glacier.

4.5. Comparing recent and former reconstructions

Four previous works had been compared with the present Rebra phase reconstruction. Regarding the cirque region we can conclude that Sawicki (1911) outlined the narrowest ice streams. In addition this early researcher estimated ice accumulation only for the lower sections of the cirques, which is a highly unrealistic approach. Gheorghiu's (2012) similar glacier reconstructions causing an underestimation of the values of pELA. My paleoglacier reconstruction agrees fairly well over the cirque region with Sîrcu (1978). The larger one is the complete tributary of Buhăescu system marked as Buhăescu Mic. Here the figure pictured by Sawicki (1911) and Sîrcu (1978) are in clear contradiction. My new field investigation indisputably confirm that the area was glacially sculptured hence reinforce Sawicki's (1911) opinion. All reconstructions leave ice free the small cirque under Piatra Alba peak. There is an extremely high uncertainty at the terminus of glaciers of Buhăescu valley, at the upper glacier limit and at the glacier confluences.

In the study of Gheorghiu (2012) the Buhăescu Valley is under-represented. Several glacier extents were made without the use of marginal forms, or even numerical modelling of the character is completely justified plateau glacier missing. Reconstruction of 18 ka can be paralleled to Rebra phase.

All former works show glacial accumulation forms in the lower part of Pietroasa Creek in different altitudes. Based on field observations, glacial-geomorphological relationships and GIS analysis these terminal forms are fluvioglacial deposits and could transport by a surge (Evans et al., 2009) into this lower position.

4.6. Chronology assumption

Stabilization date of the terminal moraines of B2/1 and B3/1 microglaciers in Buhăescu-valley was carried out by lichenometry. The 1916 and 1879 stabilization dates confirmed by dendrochronology. Summer mean temperature reconstruction from Pinus cembra tree ring width indicates considerably cooler summers in the years 1906-1918 and 1872-78.

While Gheorghiu (2012) glacier reconstructions not always reconciled with my researches, yet exposure ages correspond my investigations. Glaciers of Zănoaga Mare phase represent Younger Dryas, while glaciers of Buhăescu Mare phase 12.5 ka, Iezerele Buhăescu phase 13.5 ka and Zănoaga Iezerului 16.7 ka. Rebra phase stabilized at around 18.3 ka. In my opinion, moraines of Rebra phase were evolved during the global LGM (Last Glacial Maximum), however, because of the cool climate glacier ice did not melt immediately, so the exposure ages show the final stabilization of moraines.

The LGM atmospheric circulation was slightly different from today. Originally winter north westerly jet stream distorted because of the Fennoscandian Iceshield. A moist, unstable air masses north from the Mediterranean region supply moisture the Carpathians.

4.7. GIS conclusions

In my research I presented that GIS became an indispensable part of the classic geomorphology. Larger areas can be surveyed, data processing is faster and the results are more accurate by application of GIS. It is possible to run iterative models, and testing method suitability. Rodna Mountains study area can be interpreted as a pilot area where GIS methodology that contains logic models developed and documented so adoptable to the whole mountain range and to other mountain areas.

5. Theses

1. Detailed glacial-geomorphological survey carried. The glacial / periglacial landform mapping in the fieldwork confirmed that former studies are unreliable so reinvestigation is highly recommended.
2. The selected sample site provides unusually well-preserved moraines, so suitable for glacial environment reconstructions.
3. Four different methods used for ELA estimations and statistical comparisons show that size-specific accumulation-area ratio (ssAAR) seems to be the most reliable one. The first Carpathian application of ssAAR took place here.
4. Morphostratigraphic basis provides for five glacial phases indicated by five moraine series.
5. Using field measurements and DEM to reconstruct paleoglacier surfaces which is the base of equilibrium line altitude estimations. Manual reconstruction is faster demanding less input data and can be used anywhere, while two and three-dimensional numerical modelling requires more input data but slightly more accurate.
6. The most extensive glacier extent as a part of the Rebra phase was about 5 km^2 with 4.2 km length, represented by a well-preserved terminal moraine at 1086 m in the western part of the Buhăescu valley. The smallest glacier with an area of 0.115 km^2 occurred during the Zănoaga Mare phase, which was characterized by cirque glaciers and active rock glaciers in particular areas.

7. The average ELA for the Rebra phase was 1765 m. For less extensive phase's ELAs rose to 1865, 1960 and 2001 m, and increased to 2025 m during the final phase.
8. My new data on paleoglacier extent were compared with former studies of Szilády (1907), Sawicki (1911) Sîrcu (1978) and Gheorghiu (2012). The terminal moraine in the lower part of the Pietroasa creek mapped by Sawicki (1911) and Gheorghiu (2012) seems to be a fluvio-glacial accumulation form of a glacier outburst flood so not an in situ form.
9. Lichenometric dating of the Buhăescu valley reconstructed microglacier moraines shows that glacial erosion was active during LIA and presented again in the beginning of the 20th century cooling periods.
10. According to Carpathian analogies and reconstructed equilibrium line altitudes, Rebra phase glaciers during are likely to represent LGM but older than Younger Dryas. Exposure ages of Rodna Mountains glacial forms (Gheorghiu, 2012) correspond well with my investigations.

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